Simulations of ion beams for NDCX-II

Dave Grote , A Friedman, WM Sharp
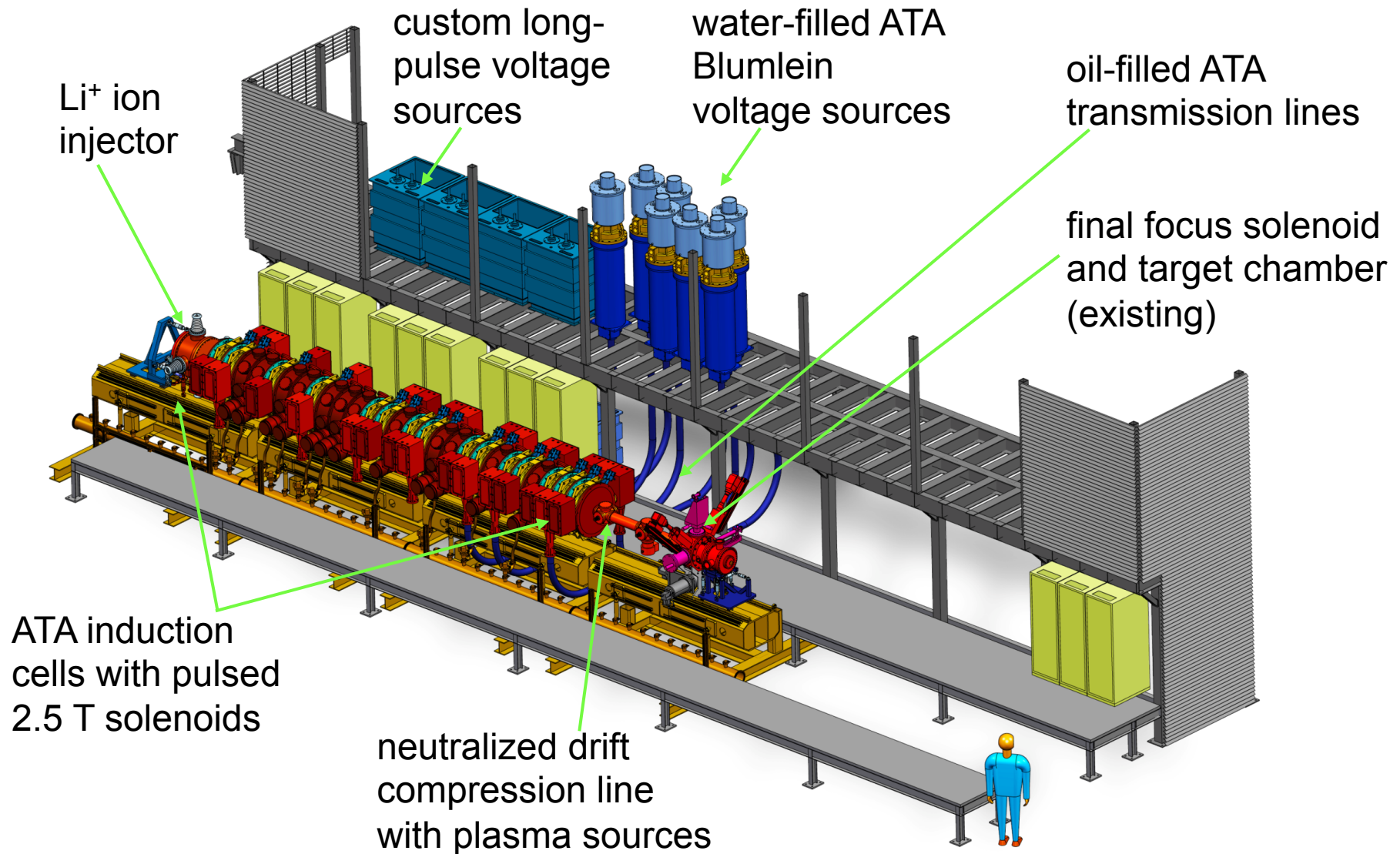
HIF2012 Symposium

LLNL-PRES-575332

Outline

- Overview of NDCX-II
  - Design and simulations
- Figure of merit for optimization and error tolerance
- Errors and optimization
  - Final focus solenoid strength
  - Timing jitter
  - Solenoid errors
- Beam plasma interaction
- NDCX-II initial results
- Conclusions and summary

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NDCX-II principal systems

Li⁺ ion injector

custom long-pulse voltage sources

water-filled ATA Blumlein voltage sources

oil-filled ATA transmission lines

final focus solenoid and target chamber (existing)

ATA induction cells with pulsed 2.5 T solenoids

neutralized drift compression line with plasma sources

NDCX-II acceleration schedule

- Inject 130 kV, 0.9 A, 400 ns, Li+ beam
- Apply correction and ~25% velocity tilt
- Initial (non-neutralized) pre-bunching to < 70 ns
- Accelerate up to 1.2 MeV
- Apply 10% velocity tilt
- Final neutralized drift compression and focus onto the target

inject → apply tilt → drift → accelerate → apply tilt → neutral-ized drift → target

- See talk by A. Friedman, Wednesday 10:00 am for more details

Potential sources of error in NDCX-II

- Solenoids:
  - Strength errors
  - Alignment errors, both offset and tilts
- Accelerating waveforms:
  - Timing jitter errors
  - Waveform errors, noise
- Source:
  - Waveform errors, noise
  - Non-uniform emission
  - Alignment errors
- Electrons (though not discussed here)
- Everything else

NDCX-II optimization

- Hardware layout is fixed
  - Source geometry (and voltage)
  - Number and arrangement of cells
  - Accelerating waveform shapes are fixed
- Variables
  - Timing of the waveforms
  - Transport solenoid strengths
  - Final focus solenoid location and strength
  - Target location
- Figure of merit
  - A measure of how well the beam drives the target, depends on beam energy, pulse duration and fluence on target
- Simulation approximations
  - Ideal plasma for ensembles

Figure of merit for error tolerance and optimization

- Figure of merit based on the beam energy, pulse duration and fluence on target

- It provides a measure of how well the beam will drive the target

$$\tau_0 = (0.42 - 0.004f)(E/2.8)$$

$$P = 0.02f(\tfrac{2.8}{E})(\tfrac{\tau_0}{\tau})\left(1 - \exp\left[(\tfrac{\tau}{\tau_0})^3\right]\right)^{\frac{1}{3}}$$

Here, f is the energy deposited in J/cm^2,
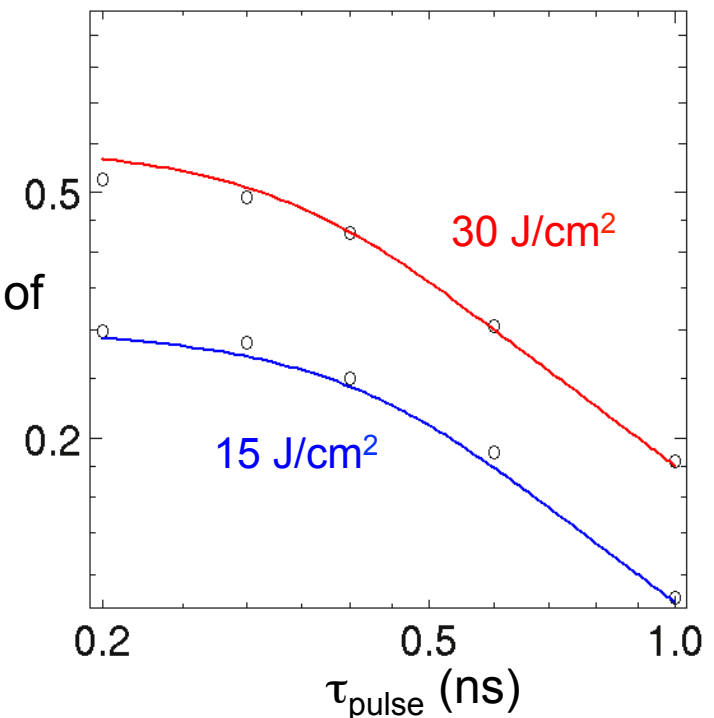τ is the FWHM pulse duration,
E is the ion energy in MeV
τ_0 roughly approximates a scale time

Figure of merit

Optimizing the final focus strength – not straightforward

- Figure of merit shows a peak with varying final focus Bz
  - Increasing Bz gives smaller spot size but longer pulse duration (due to non-paraxial pulse broadening)
  - Can be improved with a smaller beam (with reduced pulse broadening), but puts target in larger solenoid fringe field
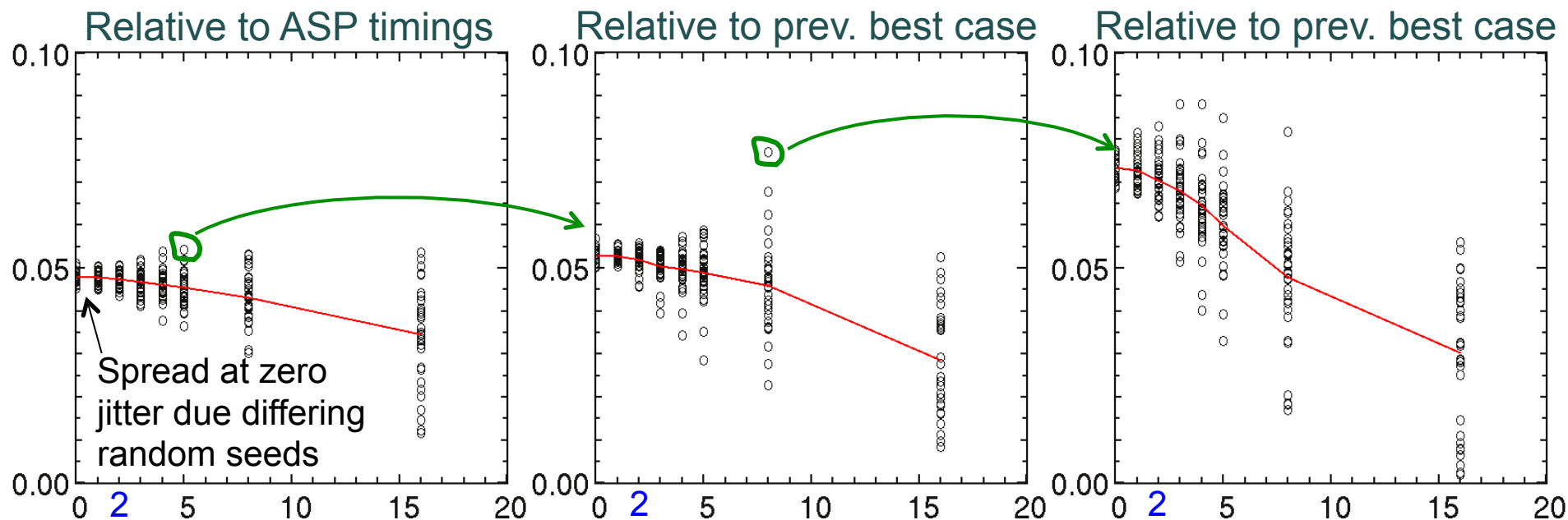

Decreasing spot size

Increasing duration

Figure of merit
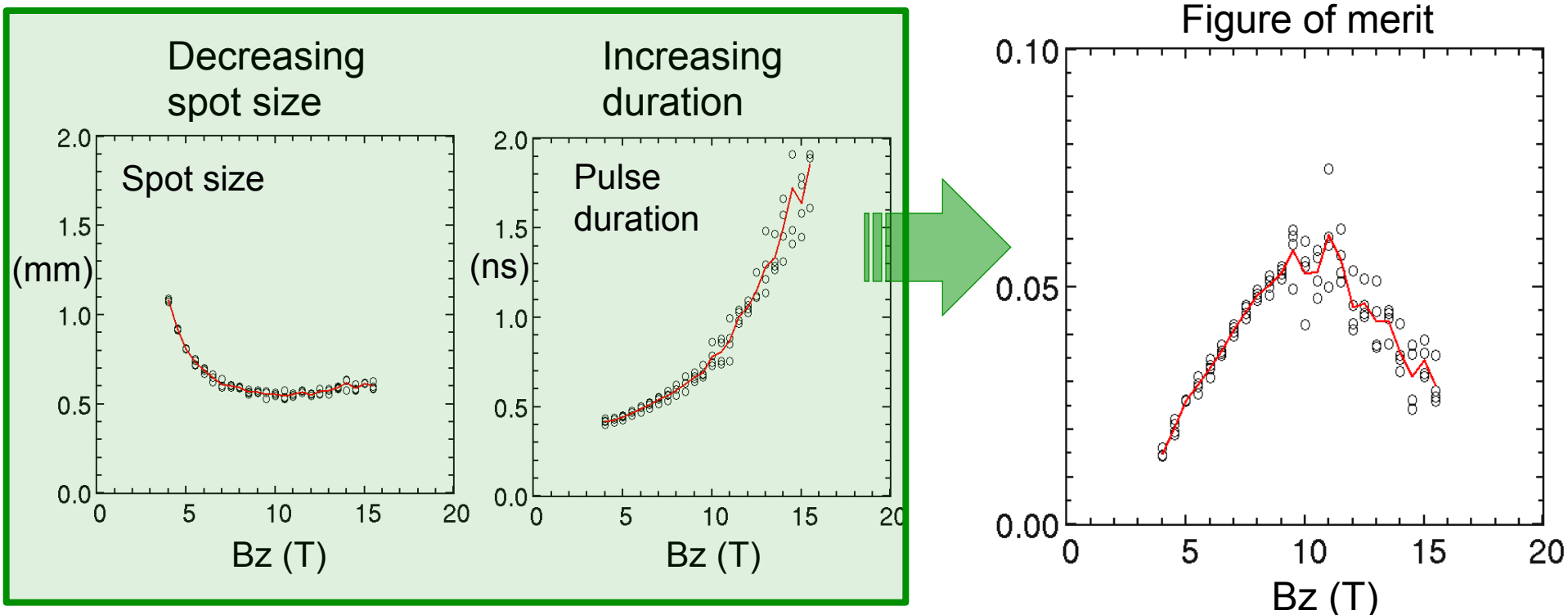
Optimizing timing of the waveforms

- The timings are originally setup with ASP simulations, but:
  - It has only an approximate description of the longitudinal self fields
  - It does not include transverse behavior and the final focus
- The timings are imported into Warp
  - The solenoids are adjusted to keep the beam collimated
  - The location of the final focus can be optimized so the peak compression and focus are coincident
  - The peak compression will generally differ somewhat from the ASP results
- Optimal cases are sought by trial and error
  - The simulations are expensive – about 1 hour each
  - Many parameters for optimization (timing for each gap)

Ensembles optimizing 12 cell design

- Ensembles were carried out with increasing timing jitter
  - Shows sensitivity to timing jitter and possible improvement
 - The expected spark gap jitter is 2 ns

Relative to ASP timings — Relative to prev. best case — Relative to prev. best case

Spread at zero jitter due differing random seeds

- Further cases showed little improvement
- Spread in results increases due to increasing sensitivity to initial conditions
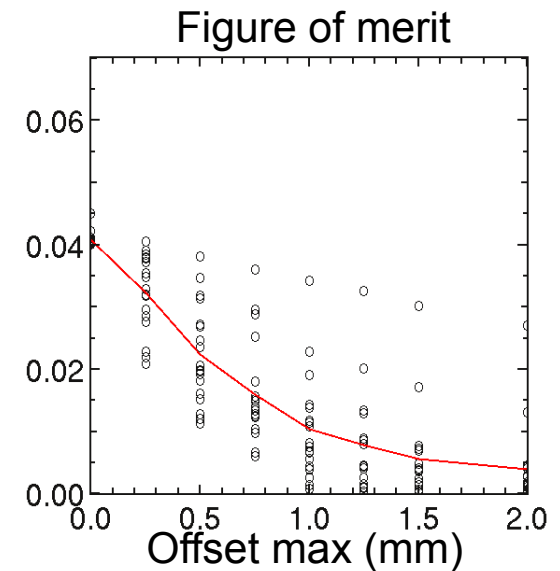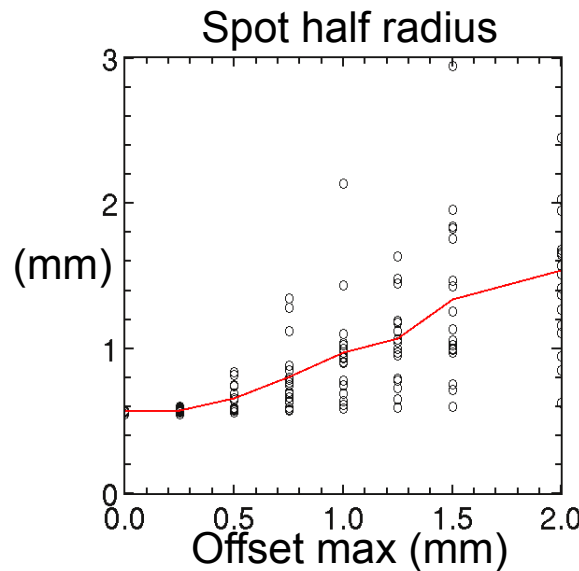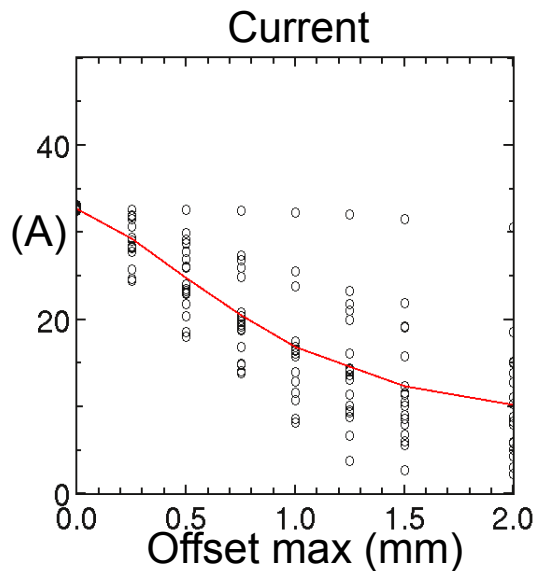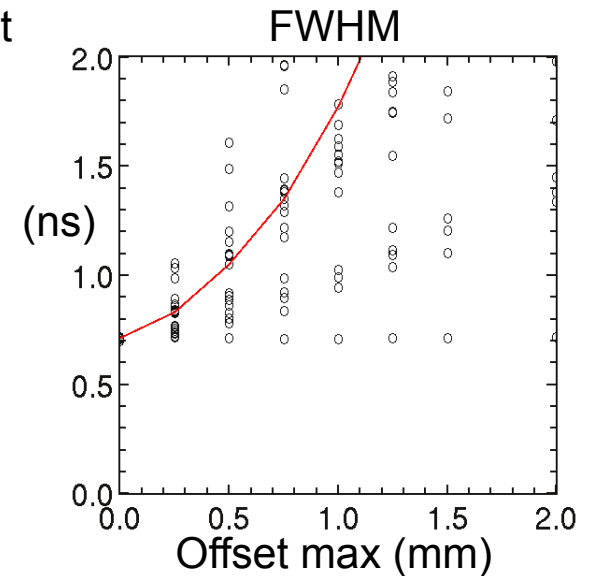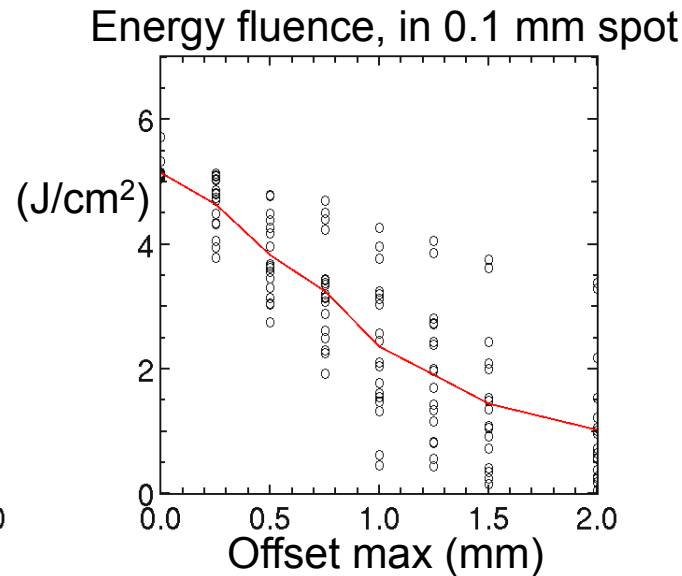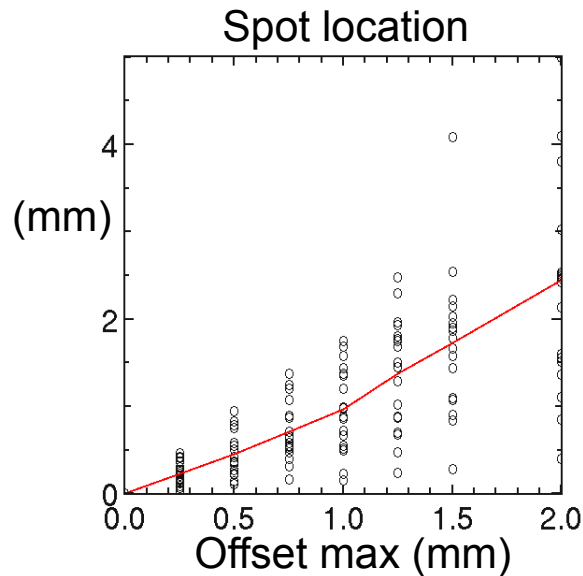
Solenoid alignment errors

- Both solenoid offsets and tilts are included
- Error measure is the maximum displacement of the ends of the solenoid
  - Each end has different offset
  - Offsets chosen randomly from a uniform distribution

- At the very least, errors must be small enough to avoid beam scraping
- Would be good to keep beam near axis in final focus (to minimize non-paraxial pulse stretching)
- Would be better to keep beam centered on target
- Would be best to minimize degradation of spot size and shape

Example deposition patterns on target

- The beam deposition patterns for three different realizations of the solenoid offsets, with 0.5 mm max offset

- These give an idea of what distortions might be seen

- Red circle includes half the deposited energy

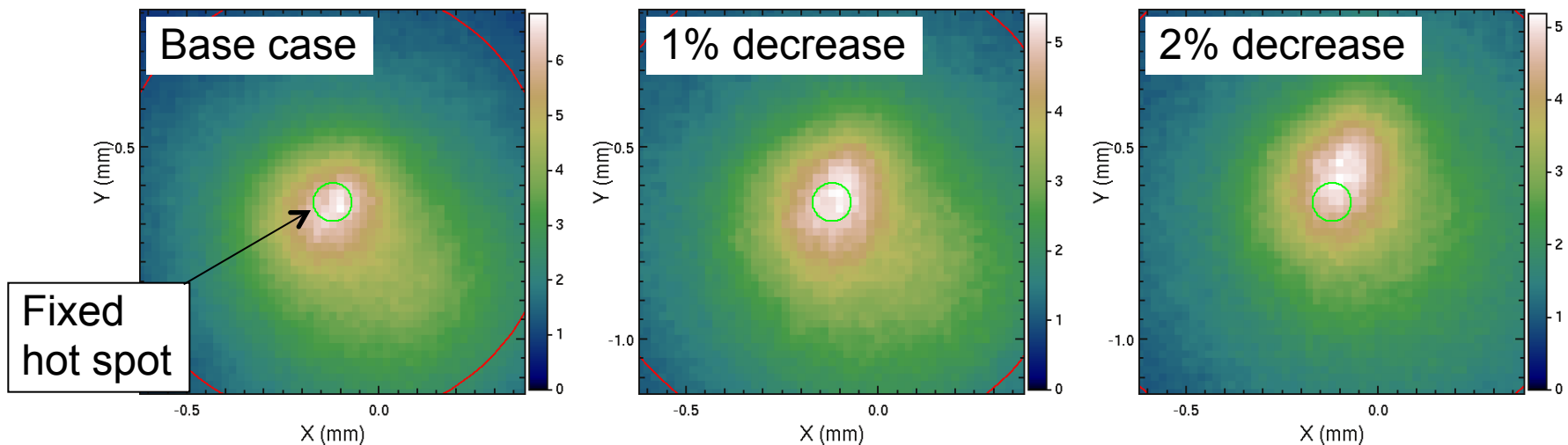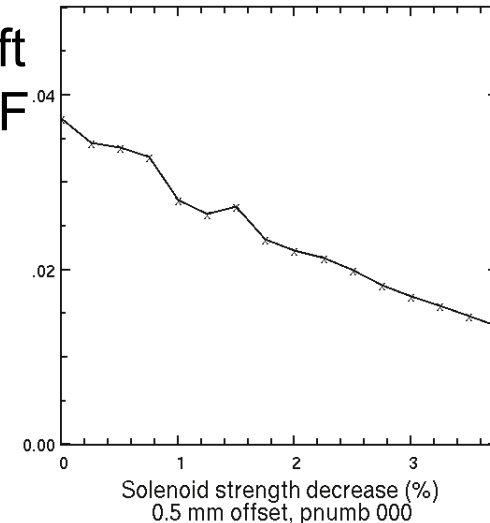- Smaller circles, with 0.1 mm diameter, are at hot spots

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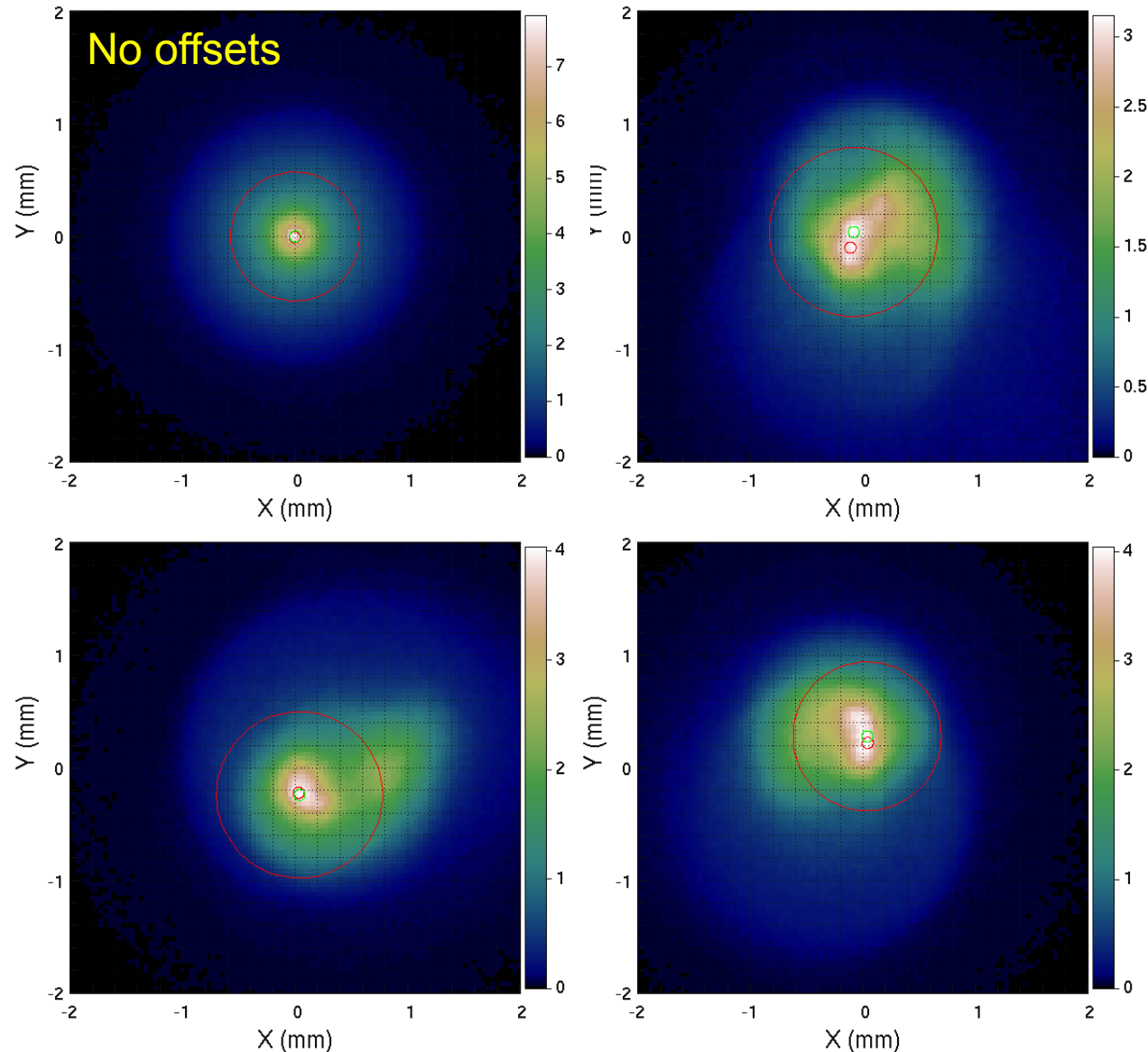
Ensembles with offsets – 0.5 mm acceptable (without steering)

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Solenoid strength error with offsets

- The solenoids can heat up, causing a decrease in Bz
- Small change in beam performance and hot spot will drift
  - Beam radius and so pulse broadening changes in FF
  - Size of offset kicks changes
- A 0.5% change is acceptable (with 0.5 mm offset)
  - Small degradation of performance
  - Drift is small compared to 0.1 mm spot size

Figure of merit

Solenoid strength decrease (%)
0.5 mm offset, pnumb 000

Base case

Fixed hot spot

1% decrease

2% decrease

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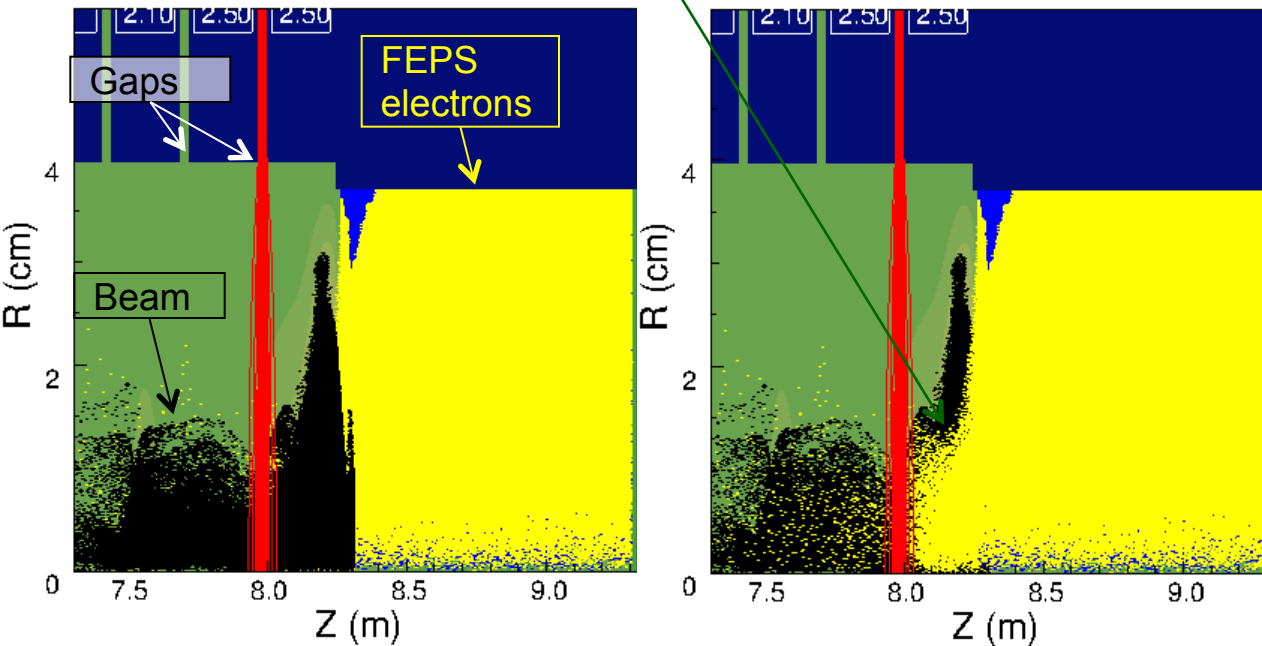# NDCX-II neutralized drift – Beam-plasma interaction

- Expect rich behavior, but is difficult to simulate at NDCX-II parameters
- Beam is slow, with $\beta \sim 0.02$
  - Wavelengths are short:
    for plasma oscillation and two-stream $\lambda \sim v_b/\omega_{pe} \sim$ few mm or smaller
  - Propagation time is long
- Want $N_p \gg N_b$ to maintain good neutralization
  - N_p set by peak compression and focus
  - For typical values, $r_b \sim c/\omega_p$, the skin depth
  - Makes step size, $dt < 1/\omega_p$, small
  - Requires many simulation particles to reduce noise
- Electrostatic simulations require ~3000 CPU hours
- Electromagnetic simulations longer – smaller step size needed because of the Courant condition, $dt \sim dz/c_{light}$
- See talk by J. L. Vay, next, "Simulations of beams in plasmas"
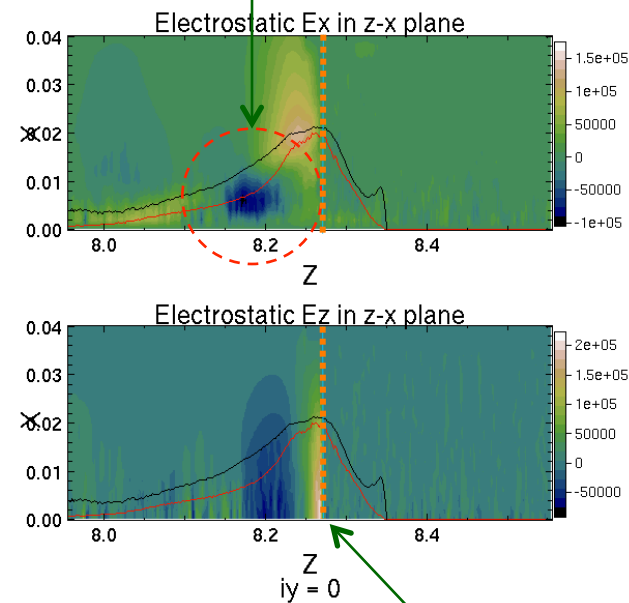
Beam pulls electrons upstream at plasma entrance

Example with FEPS $N_p = 10^{15}$ /m^3 ≤ N_b

Electrons flow upstream
Emittance growth seen only with $N_p < N_b$

From electrons streaming upstream

Same image with electrons on top

Gaps

FEPS electrons

Beam

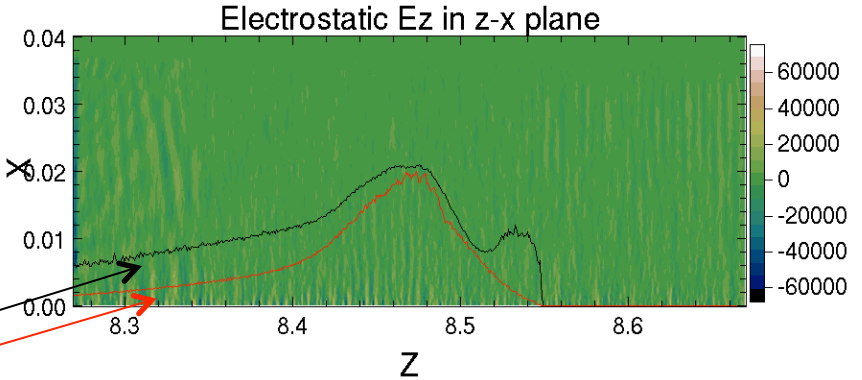Electrostatic Ex in z-x plane

Electrostatic Ez in z-x plane

Start of plasma

iy = 0

Plasma structures form in beam

Example with FEPS $N_p = 10^{16} /m^3 \sim N_b$

t = 3.94 μs

Black – beam envelope
Red ~ beam current
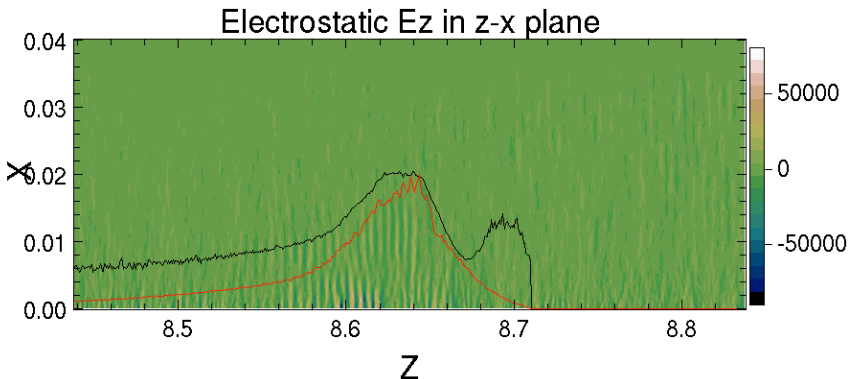
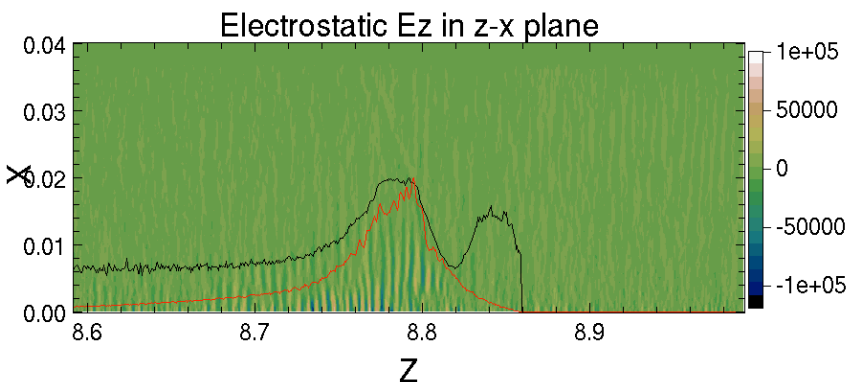Wavelength depends on density
- close to unstable e-i two-stream mode
- > plasma oscillation, ~ 1mm

t = 3.97 μs

t = 3.99 μs

Electrostatic Ez in z-x plane

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Electrons get magnetized at the FF solenoid entrance

- Bz ramps up from ~100 Gauss to ~2000 Gauss from z=9.0 to 9.2 m
- Nonlinear radial fields form
- And wave structures

t = 3.99 μs

t = 4.05 μs

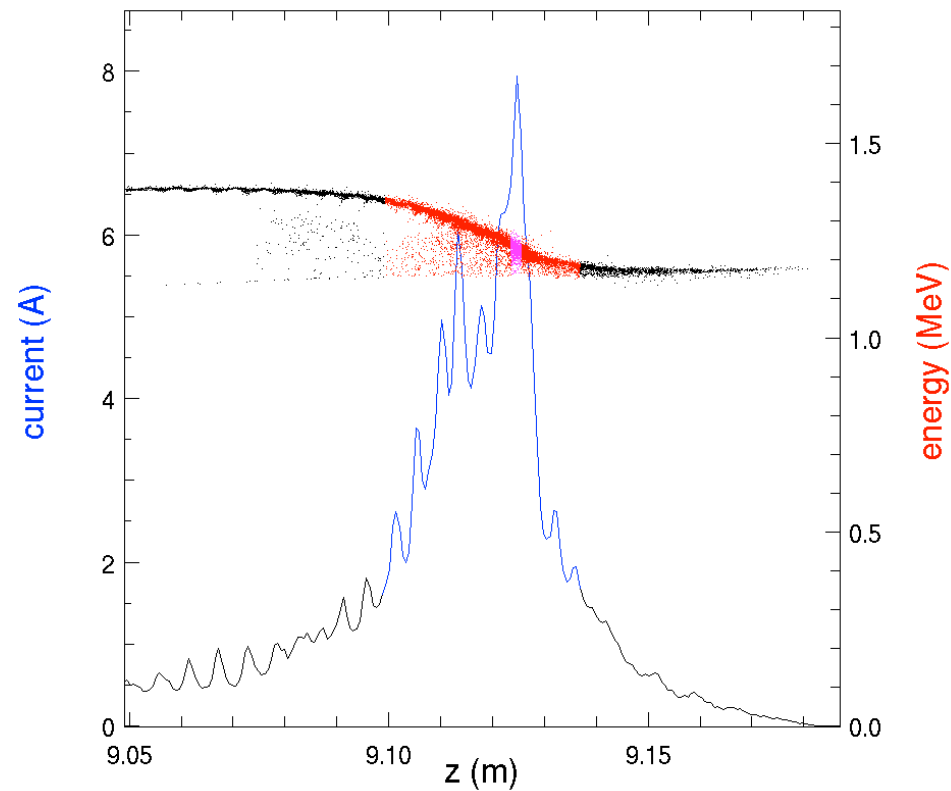**The Heavy Ion Fusion Science Virtual National Laboratory**
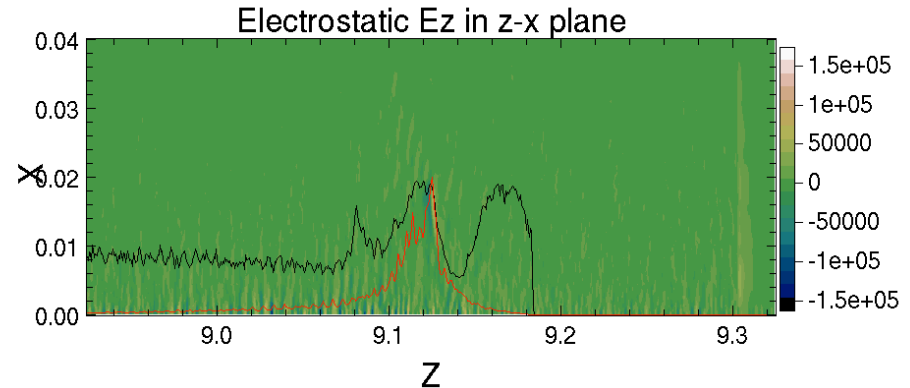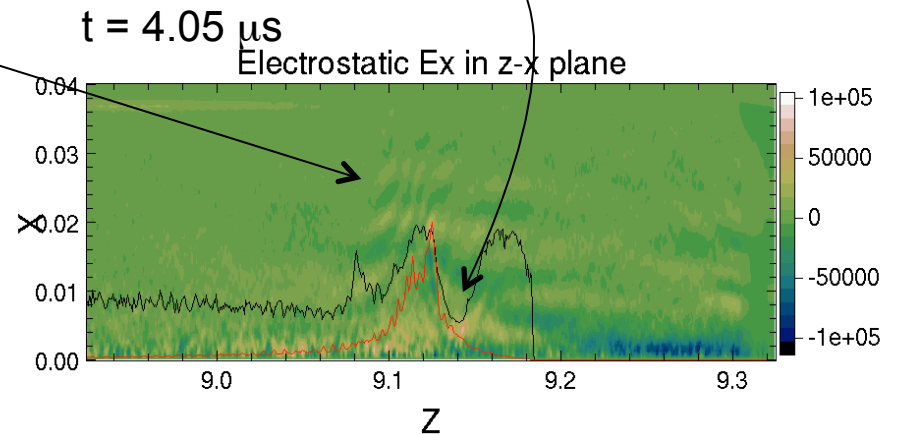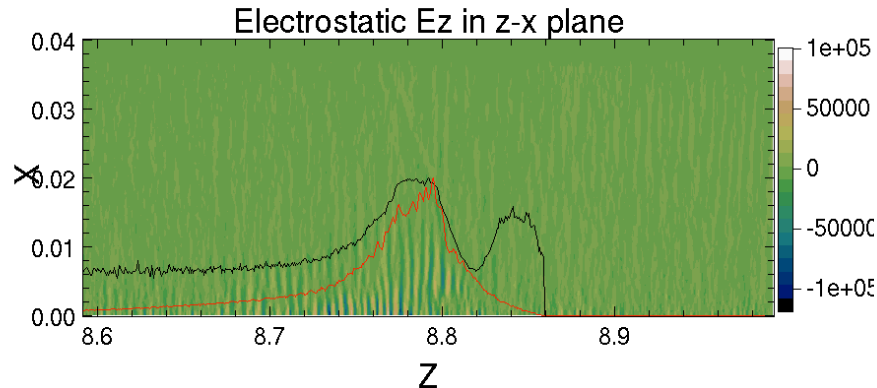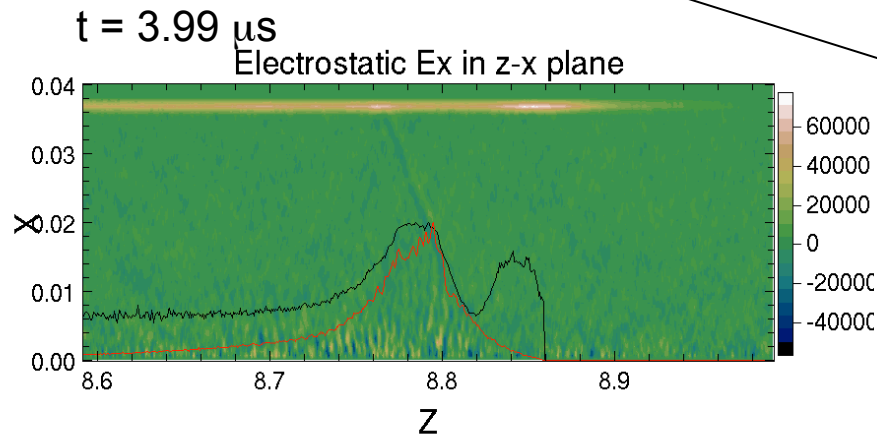
Electron-ion two stream instability in FEPS plasma

- Longitudinal structure forms on the beam
- Wavelengths comparable to most unstable mode

$$\lambda_{max} \approx \frac{2\pi v_b}{\omega_{pe}}$$

FEPS $N_p = 10^{16}$ /m³

N_p/m³	λ_{max}	Simulation λ
1×10^{16}	6.4 mm	4.4 – 5.7 mm
4×10^{16}	3.2 mm	2.8 – 3.3 mm
8×10^{16}	2.3 mm	2.2 – 2.7 mm
1×10^{17}	2.0 mm	2.5 – 2.7 mm

Performance on target

- Figure of merit with differing FEPS and CAPS densities
- Comes close to case with perfect neutralization, P = 0.054
- Sets minimum required plasma densities
  - FEPS N_p > 1×10^{15}
  - CAPS N_p > 1×10^{18}
  - These values are achievable

FEPS N_p /m^3

CAPS N_p /m^3	1×10^{15}	1×10^{16}	4×10^{16}	8×10^{16}	1×10^{17}
1×10^{18}	0.0031	0.017	0.017	0.015	0.014
1×10^{19}	0.0039	0.033	0.036	0.037	0.038
4×10^{19}	0.0045	0.039	0.036	0.036	0.036
1×10^{20}		0.032	0.054	0.032	0.028

Modeling emission from Alumina Silicate source

- Emission of Li+ from Alumina-Silicate surface characterized on STS-100
- Data can be fit to the Taylor-Langmuir expression, constrained by space charge

$$J_{TL} = \lambda_r \exp\left(-\frac{(W - dW)}{k_b T}\right)$$

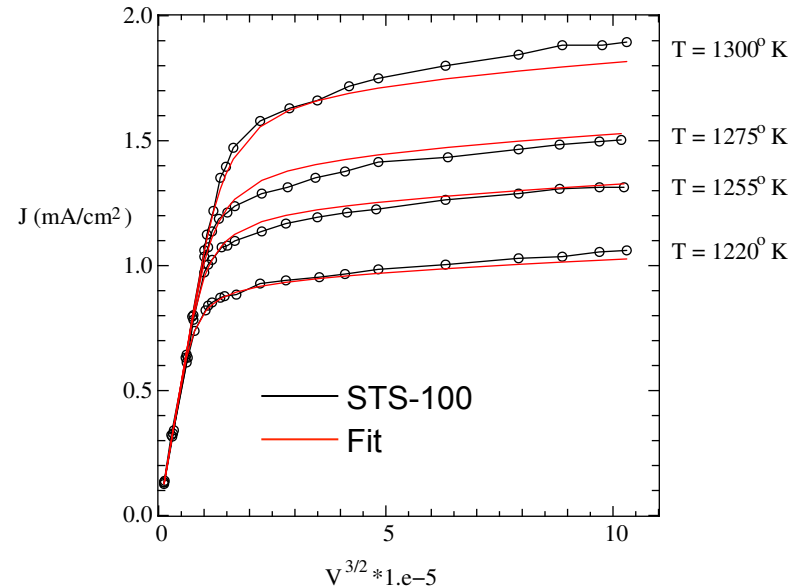$$dW = \sqrt{\frac{q^3}{4\pi\varepsilon_o} \frac{V}{d}}$$

$$J = J_{scl}\left[1 - \exp\left(-\left(\frac{J_{TL}}{J_{scl}}\right)^\eta\right)\right]^{1/\eta}$$

$$\lambda_r = 7.796e5$$
$$W = 1.478\,V$$
$$d = 1.39\,cm$$
$$\eta = 2.83$$


J (mA/cm²)

T = 1300° K
T = 1275° K
T = 1255° K
T = 1220° K

— STS-100
— Fit

$V^{3/2} * 1.e{-}5$

- The resulting λ_r and W are comparable to Taylor-Langmuir's values for cesium emission from tungsten
- See talk by P. K. Roy, Wednesday 9:20 am

# Comparison to NDCX-II initial source results

- Simulations carried to compare to NDCX-II
- Measured source waveforms used for various diode voltages
- Code emits 95% Li and 5% K
- Current profiles at fist gap location, z = 0.9 m
  - Black – space charge limited emission
  - Blue – source limited emission (Taylor-Langmuir)
  - Red – experimental results
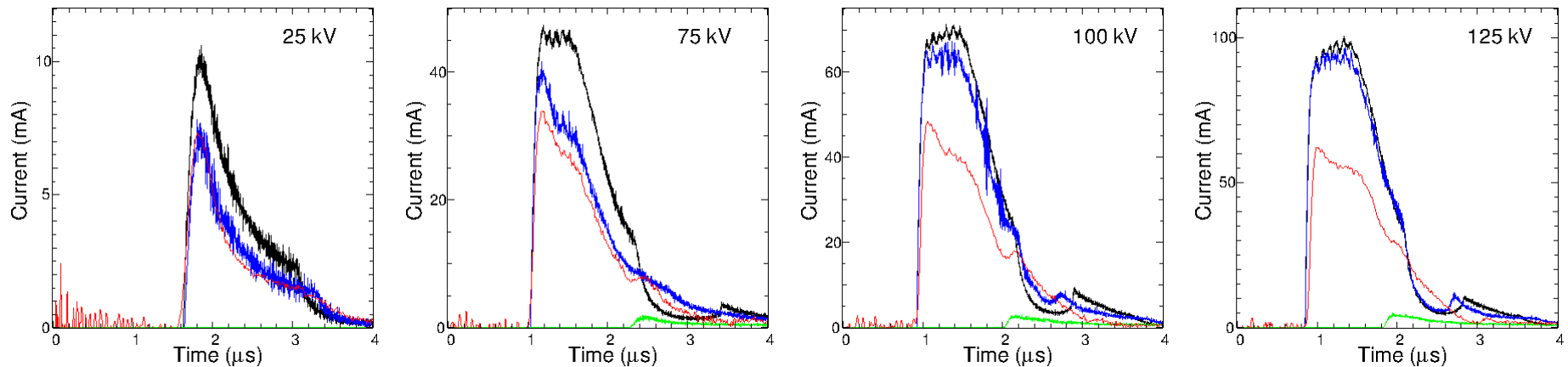
Matching to experimental results

- An ad-hoc modification of Taylor-Langmuir results in currents similar to experiment
  - $\lambda_r \rightarrow \lambda_r/3.7$
  - With 88% Li and 12% K
- Good agreement in arrival time of K pulse

Black – Li
Green – K
Blue – Li + K
Red – experiment
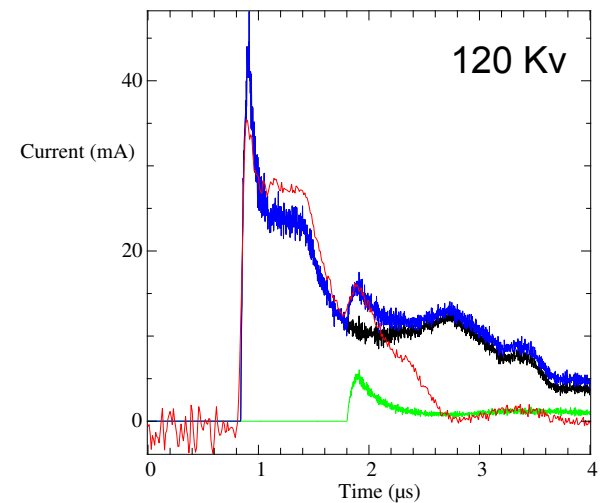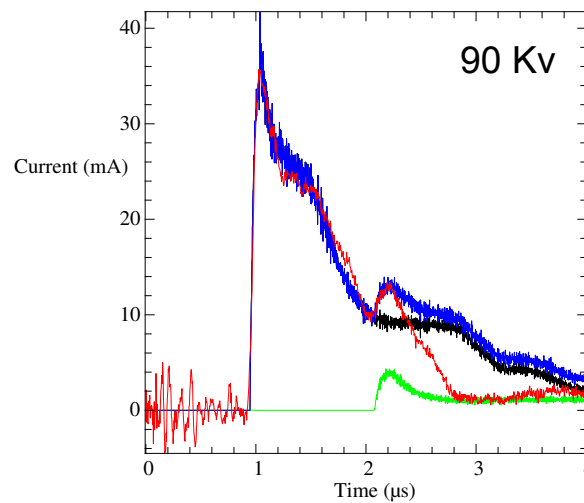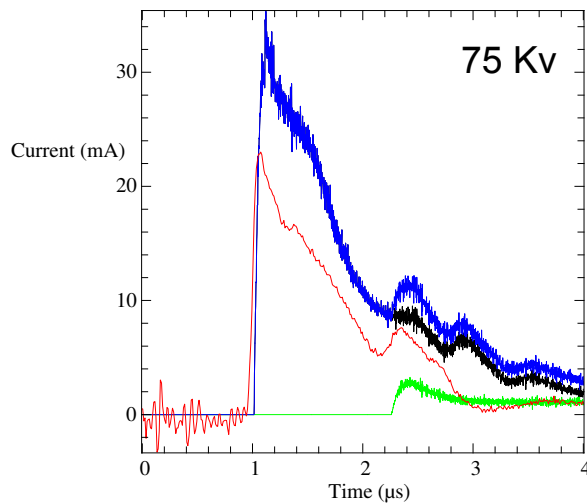
- See talk by S. Lidia, Wednesday 10:50 am

Conclusions

- NDCX-II construction for first 12 cells is complete
- The design is heavily dependent on simulation, using ASP and Warp
- Non-paraxial pulse stretching makes optimization not straight forward
- Analysis of error tolerances couples with optimization
  - Design is not completely optimized
  - Small "errors" can lead to improved designs
- Tolerances found:
  - Expected 2 ns timing jitter is well within acceptable range
  - 0.5 mm solenoid offsets tolerable and has been achieved
  - 0.5% solenoid strength errors OK
- Plasma simulations give results consistent with ideal neutralization with enough density
- Simulations are helping to characterize the initial results from NDCX-II source
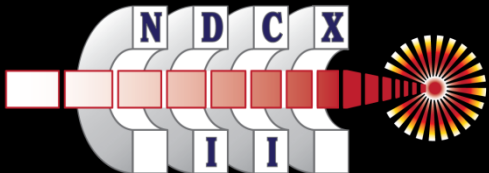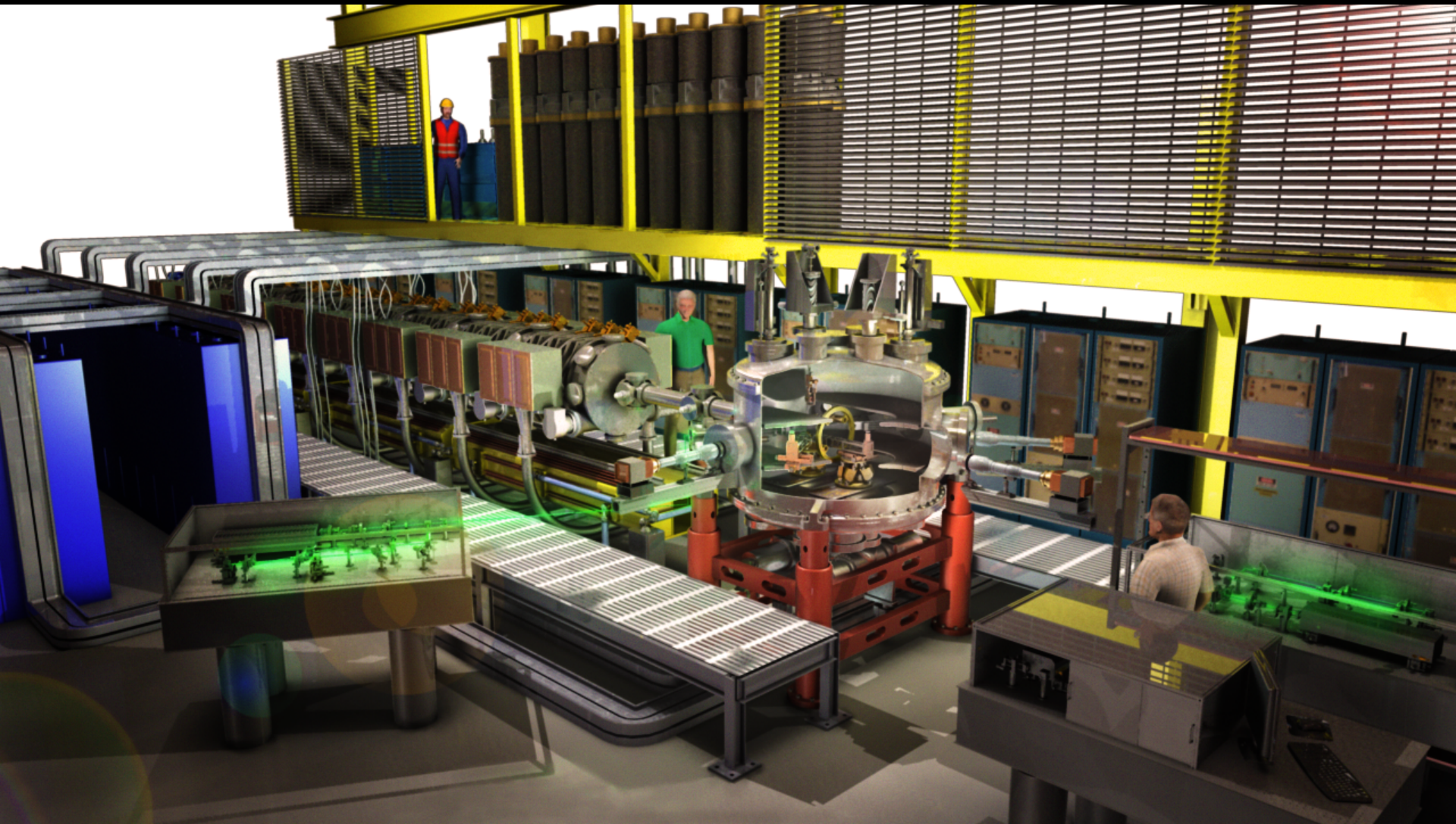
NDCX-II Warm Dense Matter Research Facility

Extras

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NDCX-II is underway at LBNL!

- DOE's Office of Fusion Energy Sciences approved the NDCX-II project earlier this year.

- $11 M of funding was provided via the American Recovery and Reinvestment Act ("stimulus package").

- Construction of the initial configuration with 15 +/- 3 cells began in July 2009, with completion planned for March 2012.
- Commissioning is to be in two 6-month phases.
- We hope to start target experiments in ~ October 2012, as we prepare for the second phase commissioning.

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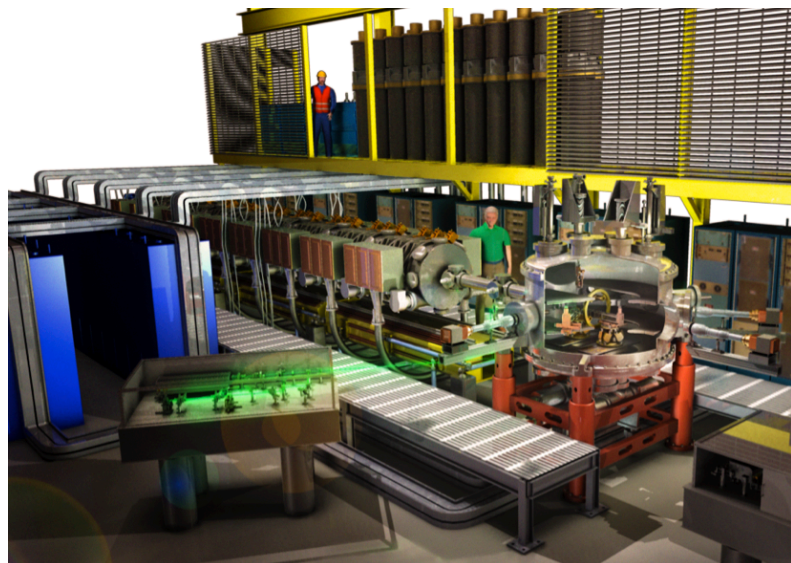
The baseline employs 12 active induction cells; we will apply any unused contingency funds to expand the scope

	NDCX-I (bunched beam)	NDCX-II construction project			NDCX-II 21-cell (enhanced)
		12-cell (baseline)	15-cell ("probable")	18-cell ("possible")	
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
Total charge	15 nC	50 nC	50 nC	50 nC	50 nC
Ion kinetic energy	0.3 MeV	1.2 MeV	1.7 MeV	2.4 MeV	3.1 MeV

The "drift compression" process is used to shorten an ion bunch

- The process is analogous to "chirped pulse amplification" in lasers
- Induction cells impart a head-to-tail velocity gradient ("tilt") to the beam
- The beam shortens as it moves down the beam line
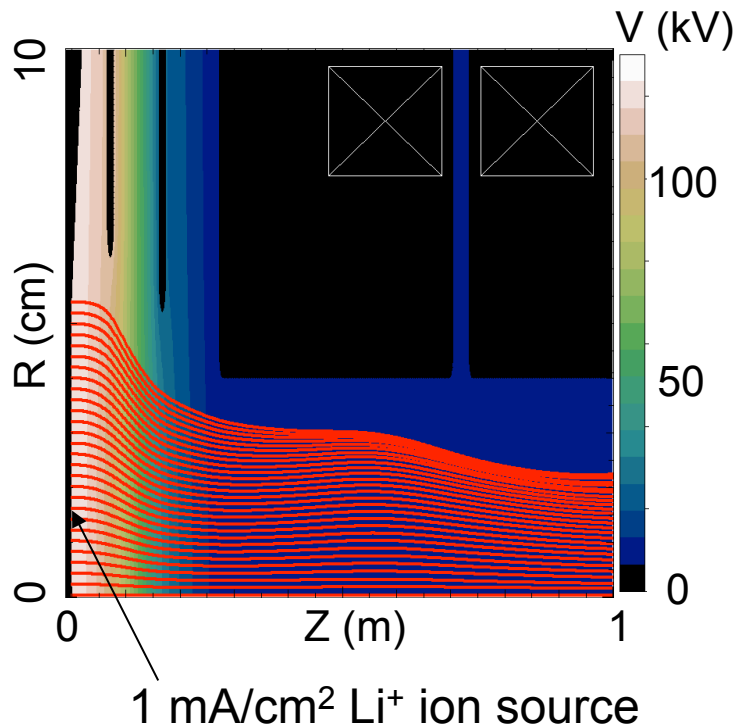 (pictures in beam frame):
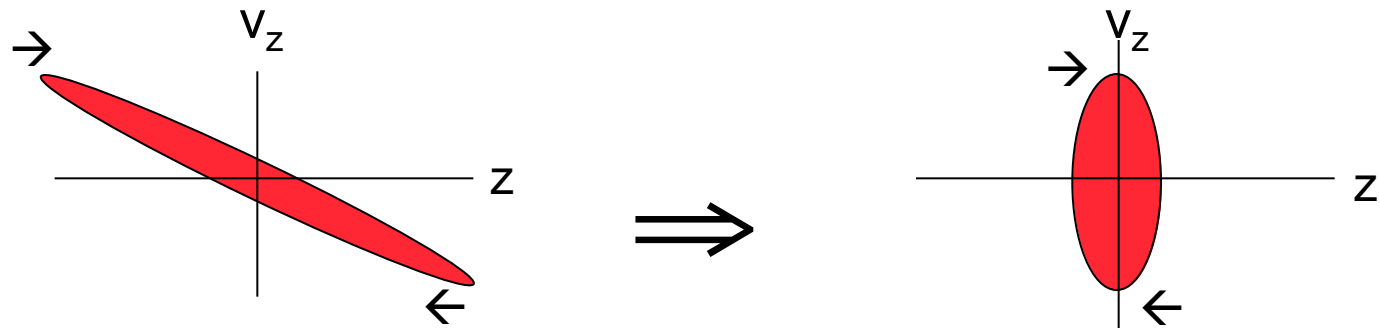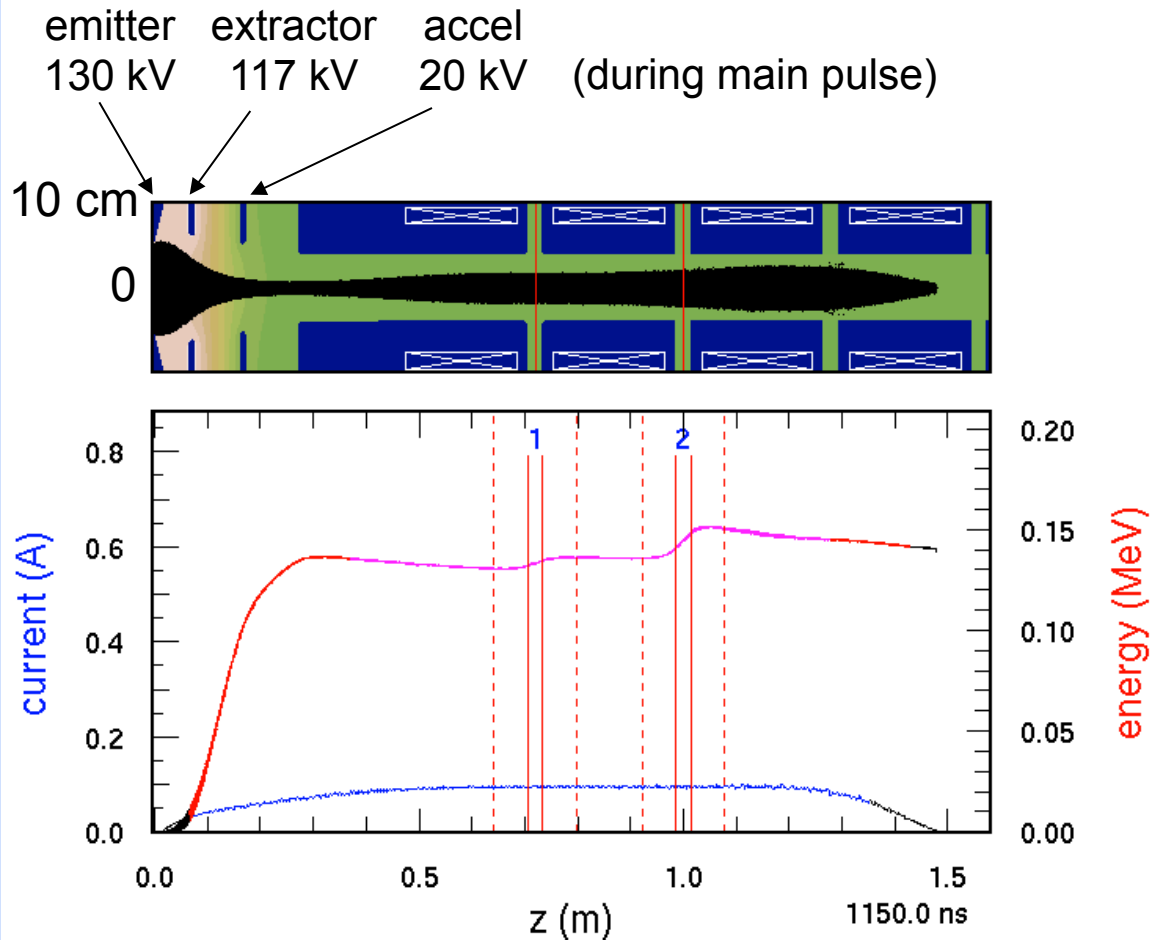

Initial beam,
with velocity tilt

compressed beam

- Space charge, if present, limits this compression
- To obtain a short pulse on target we introduce neutralizing plasma

Injector design was developed using Warp in (r,z) geometry

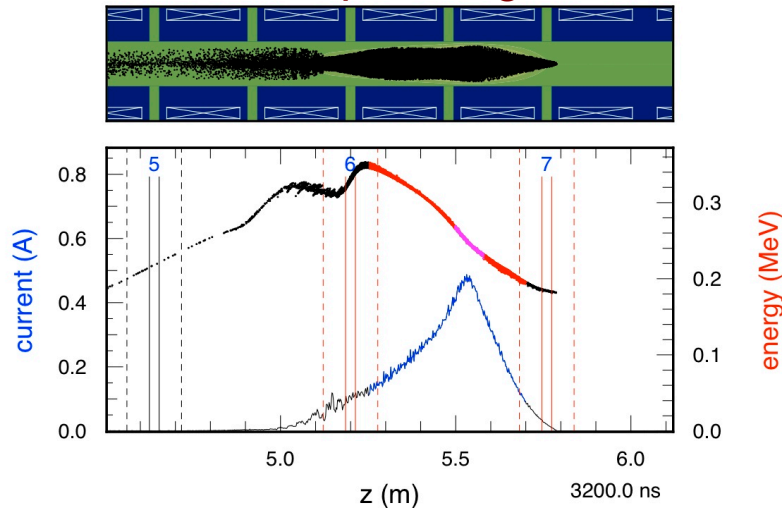**First,** used steady-flow "gun" mode to design for a nearly laminar flow:

1 mA/cm^2 Li$^+$ ion source

Second, carried out fully time dependent simulation:

emitter   extractor   accel
130 kV   117 kV   20 kV   (during main pulse)

40g-12

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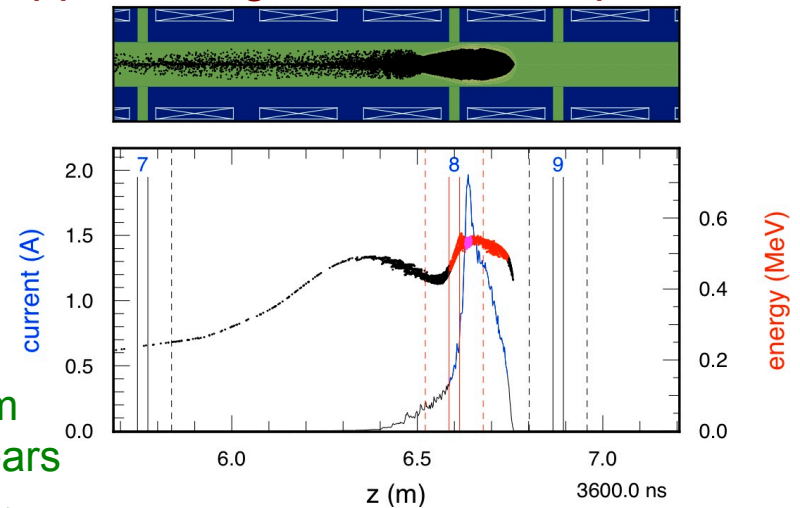
Snapshots from a Warp (r,z) simulation (18-cell version), using design generated by ASP

compressing

approaching maximum compression

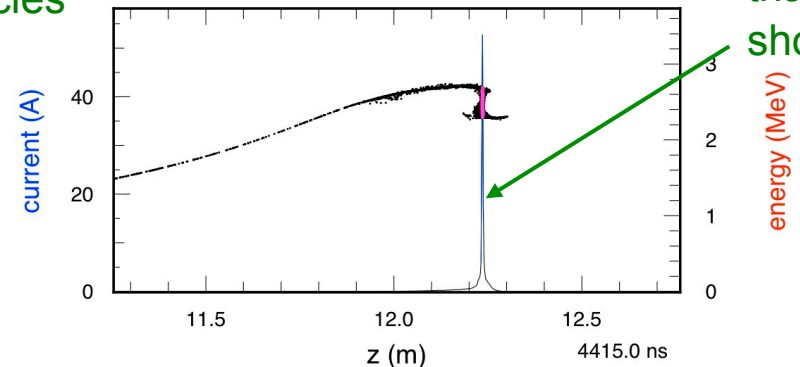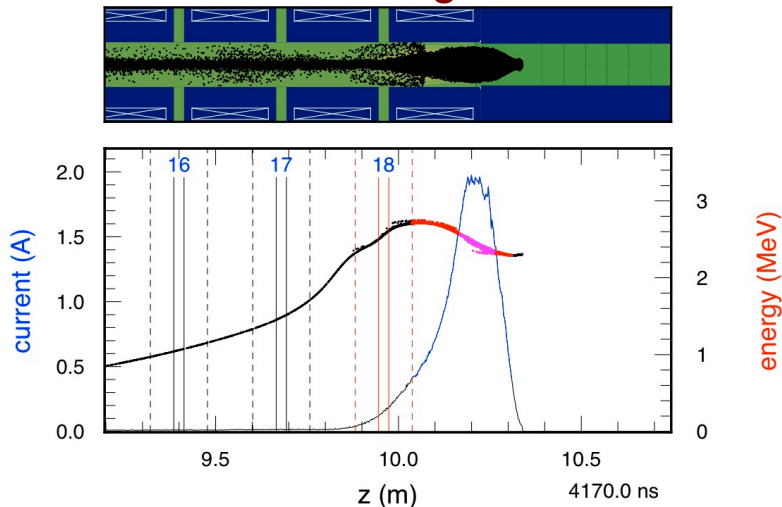Beam appears long because we plot many particles …

exiting

at focus

… but current profile shows that it is short

40h-18

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Basic accelerator schedule designed using the 1-D simulation code ASP ("Acceleration Schedule Program")

- ASP follows (z, v_z) phase space using a few hundred particles ("slices")
  - Includes longitudinal space-charge
  - Various models for accelerator waveforms

Example "Snapshots" of current and kinetic energy profiles vs. z, 120 ns into a simulated shot
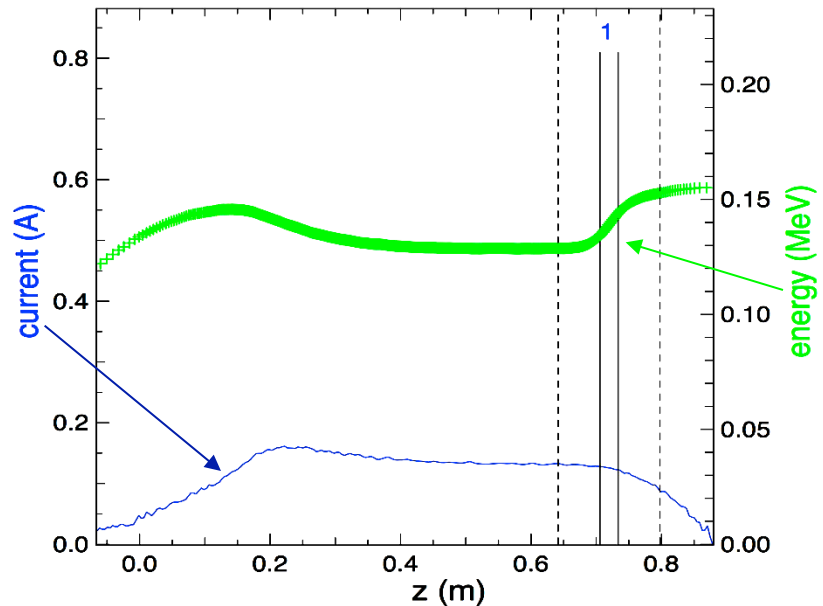
- Centroid tracking for studying misalignment effects, steering
- Optimization loops for waveforms & timings, dipole strengths (steering)
- Interactive (Python language with Fortran for intensive parts)

Final focus confounds longitudinal compression

- Non-paraxial slowing down of particles in final focus solenoid is significant compared to pulse duration

- The axial velocity of a particle in a solenoid is approximately

$$v_z \approx v_0 \left(1. - \frac{r^2 \omega_c^2}{8 v_0^2}\right)$$
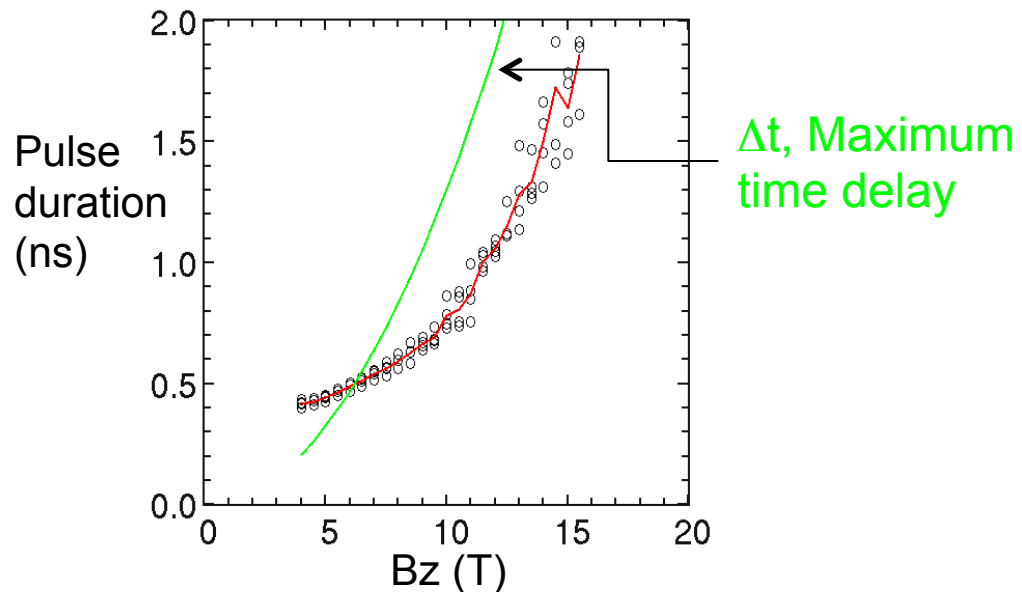
- Where v_0 is the initial velocity, r the particle radius, ω_c the cyclotron frequency = eB/m

- The particles at the outer edge of the beam see the largest delay, which is given by

$$\Delta t = \frac{L a^2 \omega_c^2}{8 v_0^3}$$

- Where L is the length of the solenoid, and a the beam radius

NDCX-II 12 cell design example

- Typical values
  - a = 2 cm
  - L = 10 cm
  - v_0 = 4.2e6 m/s
  - B = 8 T
  - Giving a delay Δt = 0.8 ns
- At the exit of the solenoid, the pulse duration is ~ 2 ns – the Δt is a large fraction of that
- At ~13 T, Δt ~ 2 ns

Pulse duration (ns)

Bz (T)

Δt, Maximum time delay

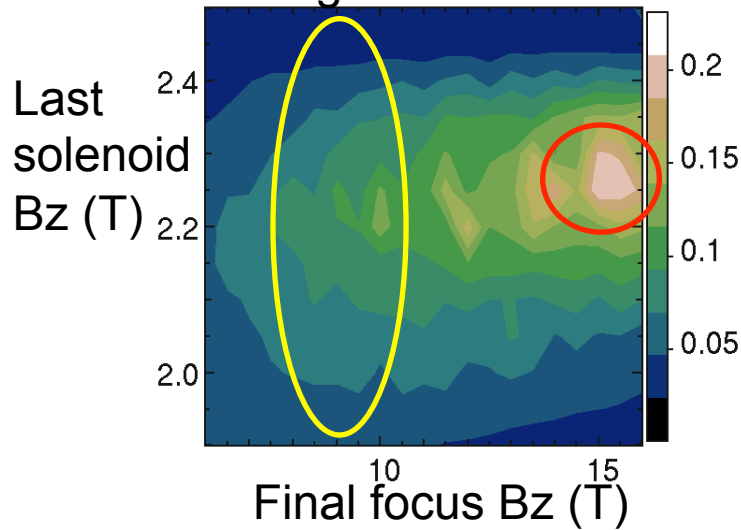**The Heavy Ion Fusion Science Virtual National Laboratory**
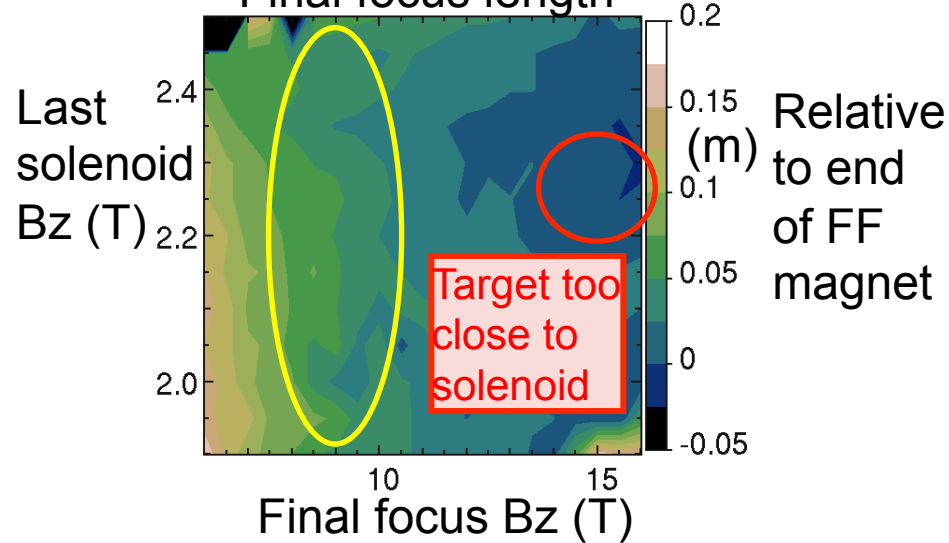
Minimizing the confounding of compression

- Unfortunately, $\Delta t \sim LB^2$, so effect cannot be reduced by changing the length of the solenoid (while maintaining the same convergence angle)
- Unfortunately, decreasing beam radius decreases the convergence angle giving a poorer spot size, but there may be a trade-off

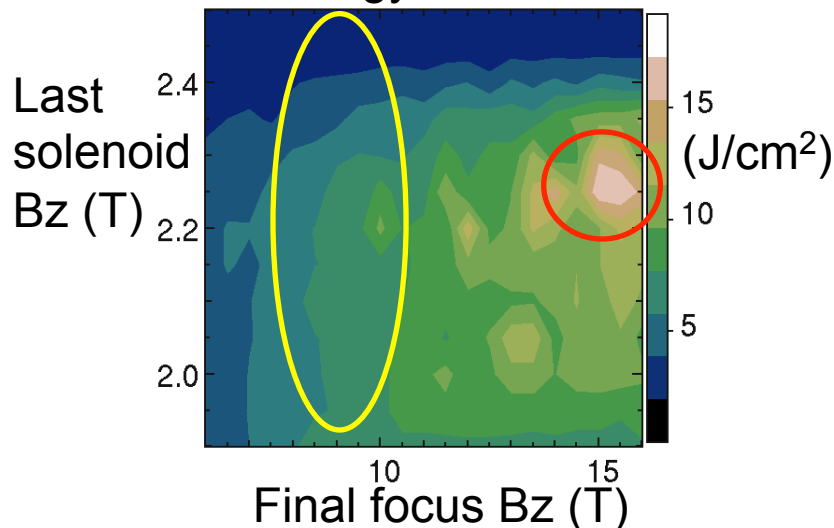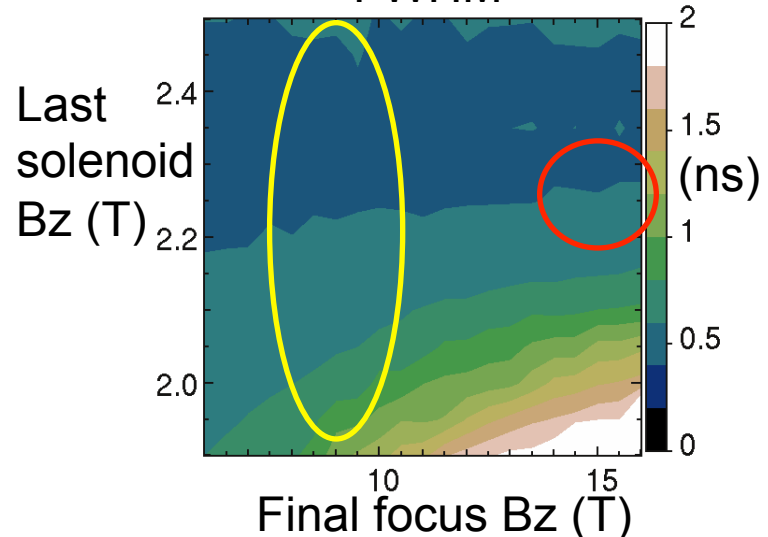# Minimizing the non-paraxial effect by minimizing the beam radius

Figure of merit

Final focus length

Relative to end of FF magnet

Target too close to solenoid

Energy fluence

FWHM

Minimizing the confounding of compression (cont)

- Unfortunately, $\Delta t \sim LB^2$, so effect cannot be reduced by changing the length of the solenoid (while maintaining the same convergence angle)
- Unfortunately, decreasing beam radius decreases the convergence angle giving a poorer spot size, but there may be a trade-off

- Fortunately, $\Delta t \sim 1/v_0^3$, so the effect diminishes at higher energy

- Note that this effect is present in the transport solenoids, but the time delay is small compared to the beam duration and is further reduced by the compression ratio.

# Ensembles for 15 cell design – similar optimization path
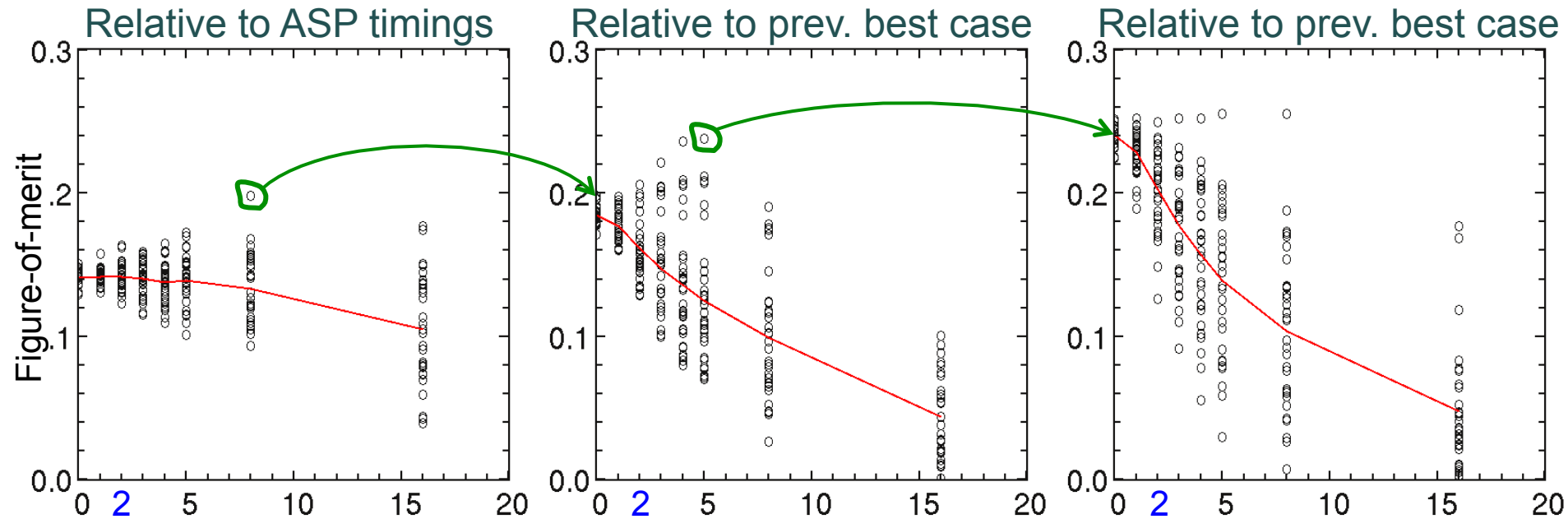
- **Nominal NDCX-II spark-gap jitter is 2 ns**
- Caveat emptor – better performance can be found using this optimization, but designs become less robust to jitter

Example, 12 cell with multivariate optimization

- A genetic optimizer (call Evolution) was used, using 8 cases per generation

- But, too many parameters (12 cell timings) so process was mostly random, but did turn up a good case

This shows the evolution of the figure of merit. The red curve, the average, does show slight increase, but best cases are mostly found randomly. The number of simulations was comparable to the random optimization, but a somewhat better case was found. However…

Figure of merit
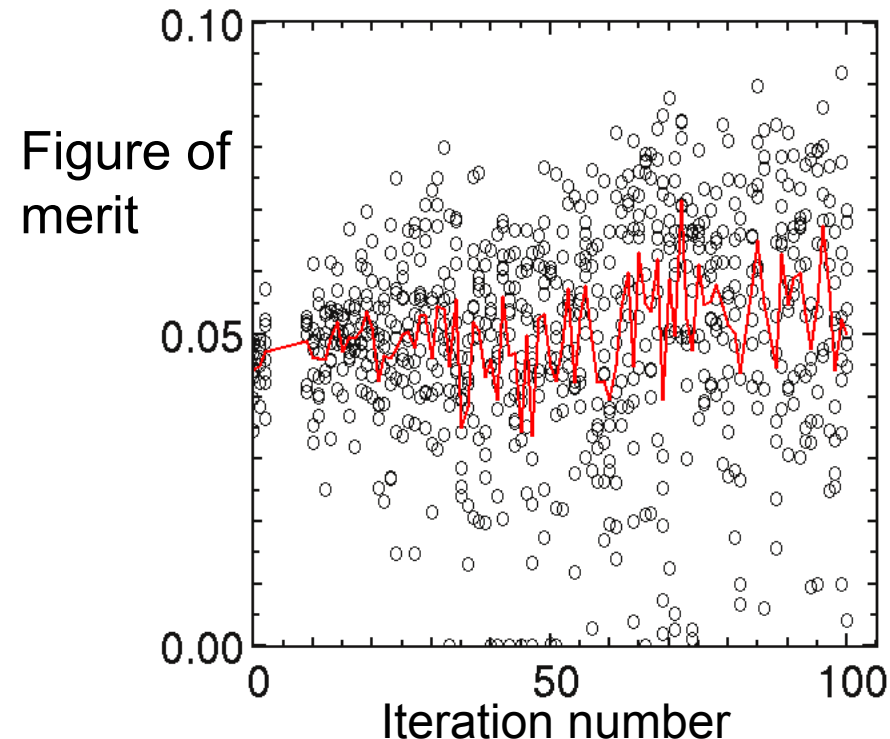
Example 12 cell with multivariate optimization, cont.

- The case that was found seems very sensitive to the initial conditions

Note the large spread for the case with no jitter (where spread is entirely due to particle random number seed.

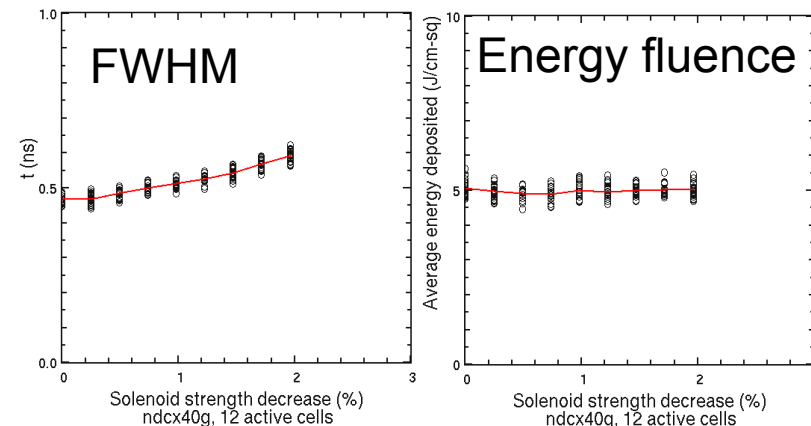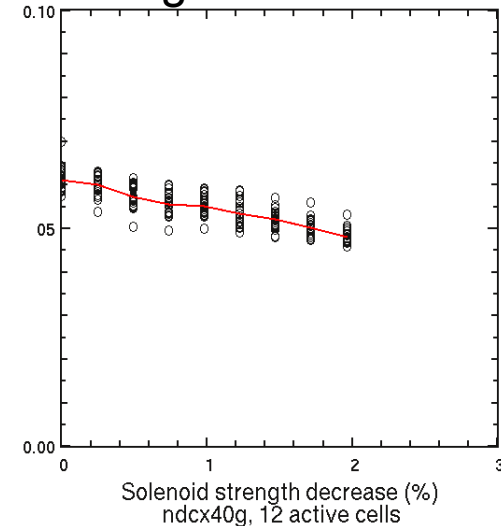**The Heavy Ion Fusion Science Virtual National Laboratory**
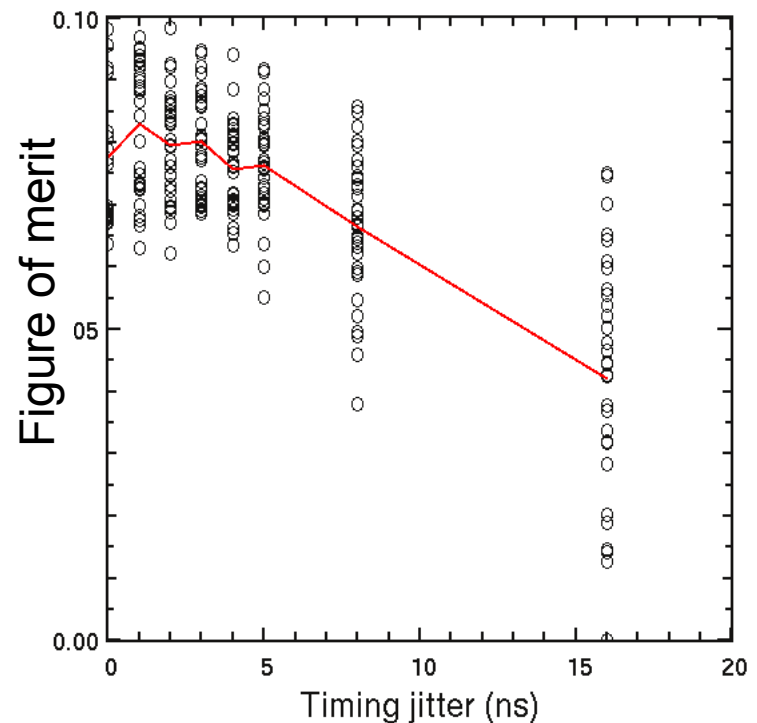
Further optimization

- The transverse size of the beam couples to the longitudinal behavior, so changing beam radius (by adjusting transport solenoids) may offer some further leverage for optimization (maybe by giving a nicer longitudinal profile).

  - Optimization complicated by other effects, e.g. non-paraxial pulse stretching, offsets
  - Optimization would be difficult – there are many parameters.

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Solenoid errors due to varying magnet temperature

- With multiple shots, magnets heat up, increasing resistance and leading to a small decrease in field strength
- With all solenoids drifting the same amount, a 0.5% change seems acceptable
  - This gives a relatively small change in target performance
  - The figure of merit decreases with increasing solenoid strength since the beam radius is larger in the final focus solenoid, increasing the non-paraxial pulse stretching

Figure of merit

Solenoid strength decrease (%)
ndcx40g, 12 active cells

FWHM

Solenoid strength decrease (%)
ndcx40g, 12 active cells

Energy fluence

Solenoid strength decrease (%)
ndcx40g, 12 active cells

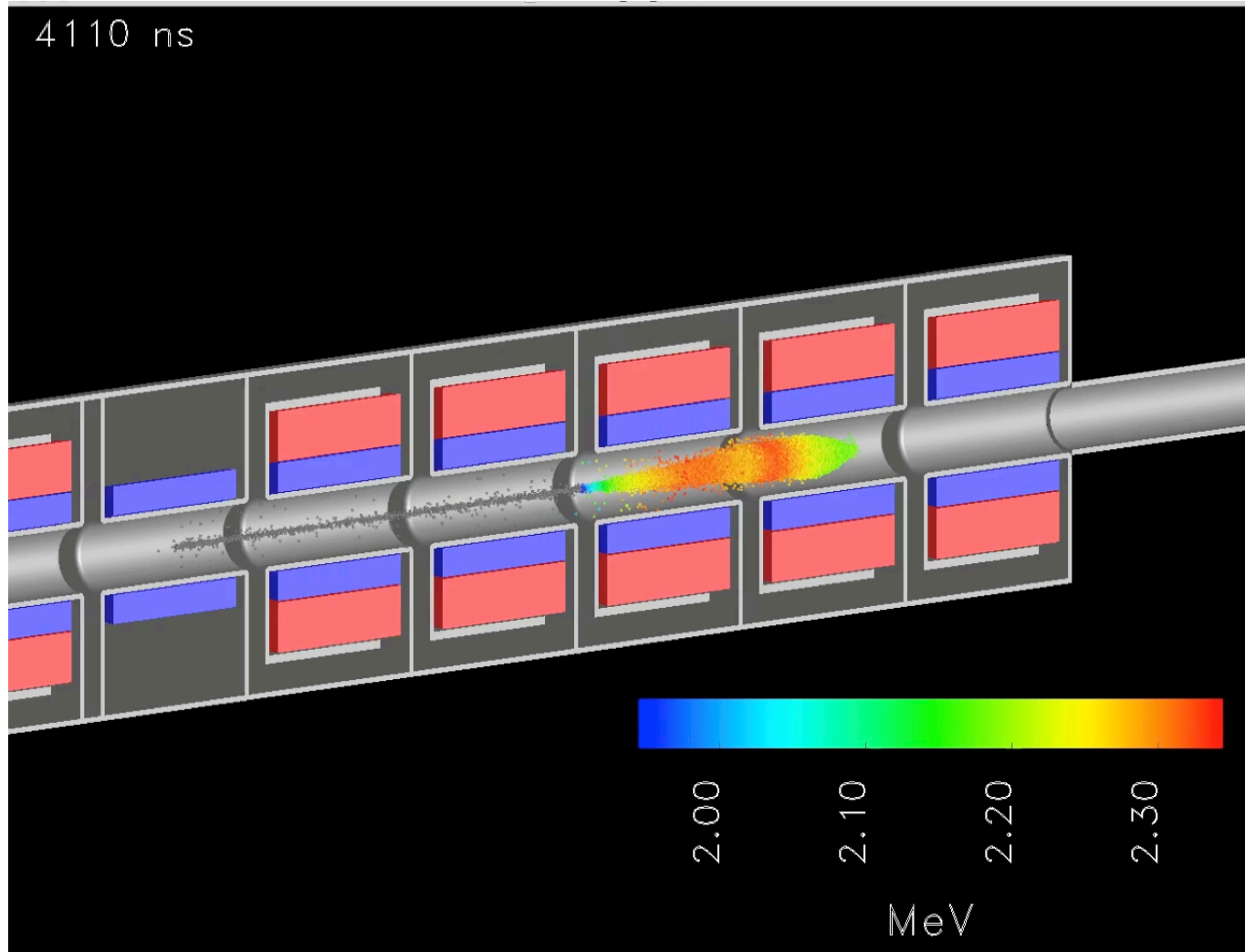**The Heavy Ion Fusion Science Virtual National Laboratory**

Solenoid strengths errors with offsets

- With both solenoid offsets and varying solenoid strengths, the location of the hot spot on target will drift
  - The size of the transverse offset kick in each magnet changes, changing the path of the beam centroid
  - The drift needs to be small enough so that the hot spot stays near the diagnosed spot on the target
- A 0.5% change in solenoid strength (with a max of 0.5 mm offset) seems reasonable
  - The hot spot drifts roughly 0.1 mm per % field strength change
  - In a 0.1 mm radius fixed spot, the deposited energy can decrease by as much as 10 to 15%

Solenoid strength error with offsets

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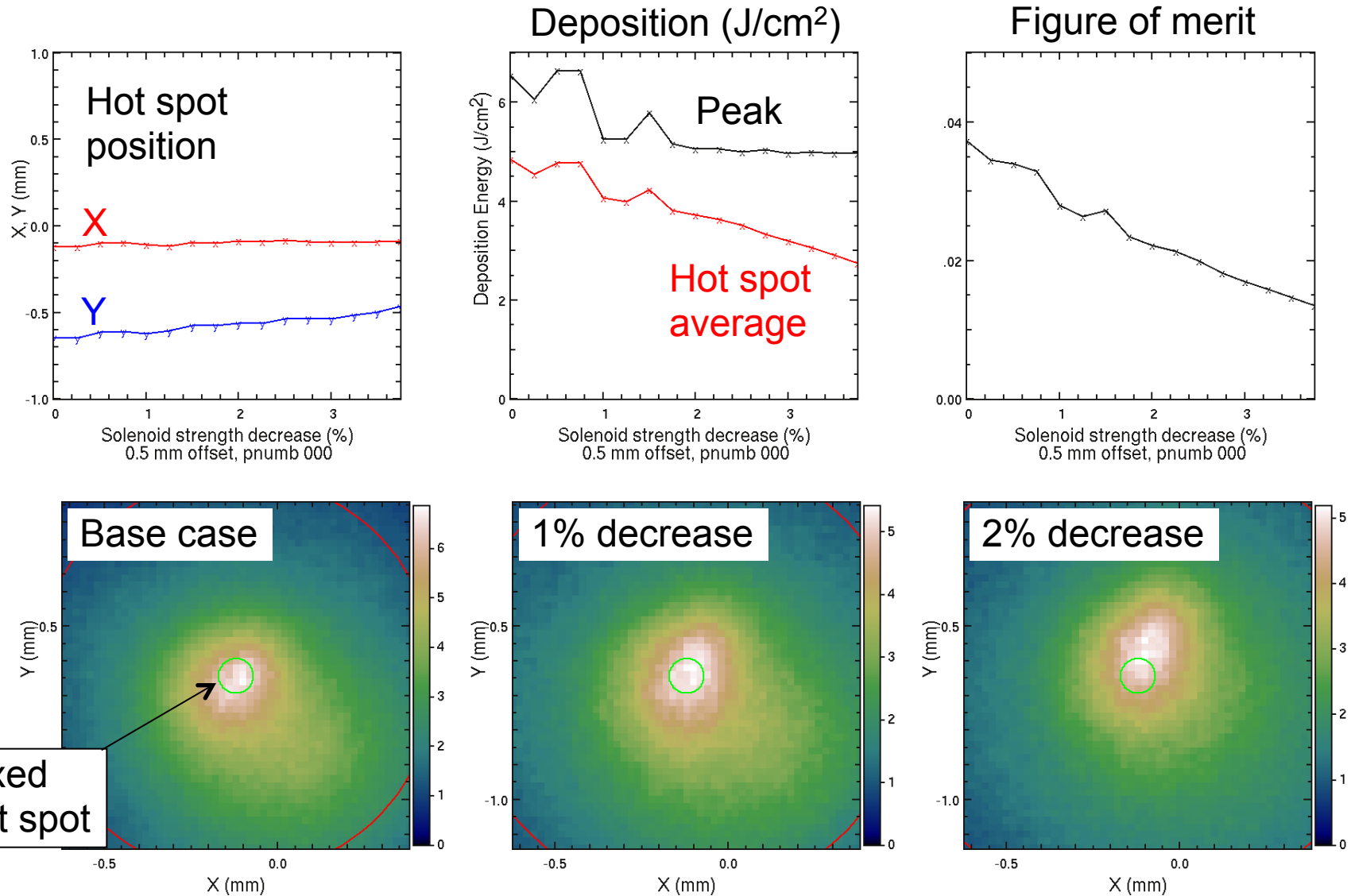
Video: Warp 3D simulation of 18-cell NDCX-II, with random offsets of solenoid ends by up to 2 mm (0.5 mm is nominal)

play video

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